REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	28 February 1995	Final Report

4. TITLE AND SUBTITLE

Control of Two and Three-Dimensional Wake Instabilities from Bluff-Bodies

5. FUNDING NUMBERS

N00014-90-J-1510

6. AUTHOR(S)

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533640 Final

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The detailed, instantaneous flow structure of the near-wake of a cylinder subjected to various classes of active (open-loop) and passive control has been characterized using both qualitative flow visualization and high-image-density particle image velocimetry (PIV) developed in our laboratories. The first cinema PIV system allows acquisition of images that are highly resolved in both space and time. Concepts of timing of vortex formation, period-doubled patterns of vortices, and modulated and phase-locked systems of vortices are addressed for controlled oscillations of the cylinder. Three-dimensional patterns of instantaneous vorticity allow classification of the modes of response of the near-wake, providing a basis for formulating concepts for attenuation of vortex formation.

14. SUBJECT TERMS

Vortex formation, particle image velocimetry

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

FINAL REPORT
(February 28, 1995)
"Control of Two and Three-Dimensional Wake Instabilities from Bluff-Bodies"

1. **GRANT TITLE:** CONTROL OF TWO AND THREE-DIMENSIONAL WAKE INSTABILITIES FROM BLUFF-BODIES.

   PRINCIPAL INVESTIGATOR AND INSTITUTION: PROFESSOR DONALD ROCKWELL, LEHIGH UNIVERSITY

2. **TOTAL FUNDING AND TERM OF RESEARCH:** $509,267 FOR A PERIOD 1 DECEMBER 1989 TO 30 JUNE 1994 (*includes no-cost extension*).

3. **RESEARCH OBJECTIVES**

   The long-term goals of this investigation are to:

   (i) Determine the quantitative flow structure in the near-wake of a cylinder as a function of Reynolds number and relate this structure to traditional studies of empirically-determined loading on the cylinder.

   (ii) Assess various techniques for control of the near-wake structure and loading, including comparison of control measures at low and high values of Reynolds number.

   (iii) Develop new types of experimental techniques, with a focus on: high-image-density particle image velocimetry (PIV); three-dimensional image processing and construction; and pattern recognition.

   The near-term objectives are to:

   (i) Determine the changes in the instantaneous and averaged streamline topology and vorticity distributions in the near-wake as a function of Reynolds number.

   (ii) Establish the effects of three-dimensional passive and active surface control, while assessing the equivalencies of three-dimensional patterns induced by geometrical and fluid-induced surface boundary conditions.

   (iii) Determine the effect of incipient and steady-state cylinder vibration on the effectiveness of surface control techniques.

   (iv) Develop particle image velocimetry-cinematographic techniques in order to construct three-dimensional space-time images of the near-wake region.

5. PAPERS

5a. PAPERS SUBMITTED TO REFEREED JOURNALS

Chyu, C., Lin, J.-C., Sheridan, J. and Rockwell, D. 1995 "Kármán Vortex Formation from a Cylinder: Role of Phase-Locked Kelvin-Helmholtz Vortices", submitted to *Physics of Fluids*.

Lin, J.-C., Towfighi, J. and Rockwell, D. 1995 "Near-Wake of a Circular Cylinder: Control by Steady and Unsteady Surface Injection", submitted to *Journal of Fluids and Structures*.

5b. PAPERS PUBLISHED IN REFEREED JOURNALS

Lin, J.-C., Towfighi, J. and Rockwell, D. 1995 "Instantaneous Structure of Near-Wake of a Circular Cylinder: On the Effect of Reynolds Number", *Journal of Fluids and Structures* (in press).

Gu, W. and Rockwell, D. 1995 "Flow Structure from an Oscillating Cylinder with a Localized Nonuniformity: Patterns of Coherent Vorticity Concentrations", *Physics of Fluids* (in press).

Lin, J.-C., Vorobieff, P. and Rockwell, D. 1995 "Three-Dimensional Patterns of Streamwise Vorticity in the Turbulent Near-Wake of a Cylinder", *Journal of Fluids and Structures* (in press).

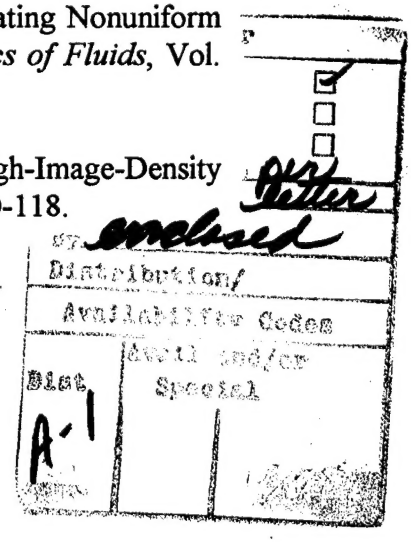
Rockwell, D. 1995 "Instabilities of Separated/Swirling Flows and Flow-Acoustic Coupling", Chapter 14 in Handbook of Fluids and Machinery (ed. J. Schetz), John Wiley and Sons (New York) (in press).

Gu, W., Chyu, C. and Rockwell, D. 1994 "Timing of Vortex Formation from an Oscillating Cylinder", *Physics of Fluids*, Vol. 6, No. 11, pp. 3677-3682.

Nakano, M. and Rockwell D. 1994 "Flow Structure in the Frequency-Modulated Wake of a Cylinder", *Journal of Fluid Mechanics*, Vol. 266, pp. 93-119.

Towfighi, J. and Rockwell, D. 1994 "Flow Structure from an Oscillating Nonuniform Cylinder: Generation of Patterned Vorticity Concentrations", *Physics of Fluids*, Vol. 6, No. 2, pp. 531-536.

Lin, J.-C. and D. Rockwell 1994 "Cinematographic System for High-Image-Density Particle Image Velocimetry", *Experiments in Fluids*, Vol. 17, pp. 110-118.



Robinson, O. and Rockwell, D. 1993 "Construction of Three-Dimensional Images of Flow Structure Via Particle Tracking Techniques", *Experiments in Fluids*, Vol. 14, pp. 257-270.

Lotfy, A. and Rockwell, D. 1993 "The Near-Wake of an Oscillating Trailing-Edge: Mechanisms of Periodic and Aperiodic Response", *Journal of Fluid Mechanics*, Vol. 251, pp. 173-201, 1993 (with A. Lotfy).

Nakano, M. and Rockwell, D. 1993 "The Wake from a Cylinder Subjected to Amplitude-Modulated Excitation", *Journal of Fluid Mechanics*, Vol. 247, pp. 79-110.

Konak, S. and Rockwell, D. 1993 "Control of the Spanwise Structure of a Bluff-Body Wake by Changes in Boundary Layer Thickness at Separation", *Physics of Fluids*, Vol. 2, pp. 509-511.

Magness, C., Towfighi, J., Akin, O., Corcoran, T. and Rockwell, D. 1993 "High-Image-Density Particle Image Velocimetry Using Laser Scanning Techniques", *Experiments in Fluids*, Vol. 14, pp. 181-192.

Nuzzi, F., Magness, C. and Rockwell, D. 1992 "Three-Dimensional Vortex Formation from an Oscillating, Nonuniform Cylinder", *Journal of Fluid Mechanics*, Vol. 238, pp. 31-54.

Nakano, M. and Rockwell, D. 1991 "Decoupling of Locked-In Vortex Formation by Amplitude-Modulated Excitation", *Journal of Fluids and Structures*, Vol. 5, pp. 455-458.

Nakano, M. and Rockwell, D. 1991 "Destabilization of the Kármán Vortex Street by Frequency-Modulated Excitation", *Physics of Fluids*, Vol. 3, pp. 723-725, 1991.

Nuzzi, F., Magness, C. and Rockwell, D. 1991 "Period-Doubling in the Wake of a Three-Dimensional Cylinder", *Physics of Fluids*, Vol. 3, pp. 1477-1478.

Gursul, I. and Rockwell, D. 1991 "Effect of Concentration of Vortices on Streakline Patterns", *Experiments in Fluids*, Vol. 10, pp. 294-296.

Gursul, I., Lusseyran, D. and Rockwell D. 1990 "On Interpretation of Flow Visualization of Unsteady Shear Flows", *Experiments in Fluids*, Vol. 9, pp. 257-266.

Staubli, T. and Rockwell, D. 1989 "Pressure Fluctuations on an Oscillating Trailing-Edge", *Journal of Fluid Mechanics*, Vol. 203, pp. 307-346.

5c. PAPERS PUBLISHED IN NON-REFEREED JOURNALS

Invited Lecture: "Quantitative Visualization of Bluff-Body Wakes Via Particle Image Velocimetry", International Union of Theoretical and Applied Mechanics Symposium on Bluff-Body Wakes, Goettingen, Germany, 1992 (to be published by Springer-Verlag: eds. H. Eckelmann and J. M. R. Graham).

Invited Presentation: "Quantitative Interpretation of Complex, Unsteady Flows via High-Image-Density Particle Image Velocimetry", SPIE (Society of Photo-Optical Engineers) International Symposium on Optics, Imaging and Instrumentation, San Diego, California, 11-16 July (to be published as SPIE Proceedings, Volume 2005)(with J.-C. Lin).

Invited Lecture: "Active Control of Globally-Unstable Separated Flows", International Symposium on Nonsteady Fluid Dynamics, ASME FED-Vol. 92 (edited by J. A. Miller and D. P. Telionis), pp. 379-394.

6. TECHNICAL REPORTS

Four Annual Reports entitled "Control of Two- and Three-Dimensional Wake Instabilities from Bluff-Bodies", submitted to ONR in the time period September-December, 1990 through 1994.

7. BOOKS PUBLISHED

Flow-Induced Vibrations: An Engineering Guide, Balkema Press, Rotterdam, The Netherlands, 1994 (with E. Naudascher).

8. NUMBER OF BOOK CHAPTERS PUBLISHED

None

9. PATENT APPLICATIONS

None

10. SIGNIFICANT PRESENTATIONS

10a TOTAL NUMBER

Fifteen

10b LIST OF TOP THREE

Invited Lecture: "Quantitative Visualization of Bluff-Body Wakes Via Particle Image Velocimetry", International Union of Theoretical and Applied Mechanics Symposium on Bluff-Body Wakes, Goettingen, Germany, 1992 (to be published by Springer-Verlag: eds. H. Eckelmann and J. M. R. Graham).

Invited Lecture: "Active Control of Globally-Unstable Separated Flows", International Symposium on Nonsteady Fluid Dynamics, ASME FED-Vol. 92 (edited by J. A. Miller and D. P. Telionis), pp. 379-394.

Invited Plenary Lecture: "Quantitative Imaging of Bluff Body Wakes", Annual Meeting of American Physical Society, Division of Fluid Dynamics, Atlanta, Georgia, November, 1994.

(Unable to accept a number of Invited Lectures and Seminars at various universities and technical meetings due to research commitments.)

11. AWARDS

Paul B. Reinhold Professorship of Mechanical Engineering and Mechanics (1988 - present)

Joseph and Eleanor Libsch Research Award (1989) (presented to Lehigh faculty member with most outstanding research accomplishments).

12. POST-DOCS SUPPORTED

Number supported: Two

Total man-months: Twenty-four

13. GRADUATE STUDENT SUPPORT

Number supported: Two

Total man-months: Eighteen

14. MOST SIGNIFICANT PUBLICATIONS (abstracts only)

"Flow Structure in the Frequency-Modulated Wake of a Cylinder", *Journal of Fluid Mechanics*, Vol. 266, pp. 93-119, 1994 (with M. Nakano).

A cylinder is subjected to frequency-modulated (FM) excitation, and the structure of its wake is characterized in terms of the modulation frequency and the frequency

deviation. It is possible to destabilize or restabilize the degree of organization of the vortical structures in the near wake, and thereby substantially manipulate the spectral content, relative to the case of purely sinusoidal excitation. These processes of destabilization and restabilization are attainable by varying the frequency deviation while holding the modulation frequency constant or vice versa. A phase-locked periodicity of the near-wake response is attainable at the period of the modulation frequency, as well as at double its period. This phase-locked periodicity, or lack of it., is related to the degree of reorganization of the wake. The structure of the far wake is strongly dependent upon the nature of the near wake modification. Either coherent or destabilized wake structure can be induced in the far wake, at a given value of nominal excitation frequency, by employing appropriate FM excitation.

"Timing of Vortex Formation from an Oscillating Cylinder", *Physics of Fluids*, Vol. 6, No. 11, pp. 3677-3682 (W. Gu and C. Chyu).

The instantaneous structure of the near-wake of a cylinder subjected to forced oscillations is examined using particle imaging, which leads to representations of the streamline patterns and distributions of vorticity. As the frequency of excitation of the cylinder is increased relative to the inherent vortex formation frequency, the initially-formed concentration of vorticity moves closer to the cylinder until a limiting position is reached; at this position, the vorticity concentration abruptly switches to the opposite side of the cylinder. This process induces abrupt changes of the topology of the corresponding streamline patterns; such topological patterns alone, however, do not properly suggest the existence and rearrangement of the vorticity concentrations. Moreover, this vorticity-switching concept persists to high values of Reynolds number, where the values of mean base pressure coefficient and vortex formation length differ substantially from those at low Reynolds number. The switching mechanism is not significantly altered, either in an instantaneous or ensemble-averaged sense, by the presence of small-scale Kelvin-Helmholtz vortices that coexist with the large-scale (Kármán) vortices.

"Flow Structure from an Oscillating Non-Uniform Cylinder: Generation of Patterned Vorticity Concentrations", *Physics of Fluids*, Vol. 6, No. 2, pp. 531-536 (with J. Towfighi).

Forced oscillation of a mildly nonuniform cylinder generates patterns of vorticity concentrations oriented orthogonally to its axis. These complex, but ordered, patterns are repeatable at subharmonics of the cylinder oscillation frequency; they therefore provide a means of identifying the first and second period-doubled states of the wake response.

"High-Image-Density Particle Image Velocimetry Using Laser Scanning Techniques", *Experiments in Fluids*, Vol. 14, pp. 181-192, 1993 (with C. Magness, J. Towfighi, O. Akin and T. Corcoran

Laser scanning, corresponding to time-dependent deflection of laser beam across a field of interest, can provide relatively high illumination intensity of small particles, thereby allowing implementation of high image-density particle image velocimetry (PIV). Scanning techniques employing a rotating (multi-faceted) mirror, an oscillating mirror, and an acousto-optic deflector are addressed. Issues of illumination in density and exposure, rate of scan of the laser beam, and retrace time of the scanning beam are assessed. Representative classes of unsteady separated flows investigated with laser-scanning PIV are described.

15. ACCOMPLISHMENTS

- The first instantaneous wholefield measurements for the near-wake of the cylinder have been obtained using unique techniques of laser-scanning and high-image-density particle image velocimetry developed in our laboratory.

- The first cinematographic technique for high-image density particle image velocimetry has been developed in our laboratories. It leads to space-time representations of instantaneous flow structure in three-dimensional space at high values of Reynolds number. By using a framing camera in conjunction with a rotating mirror concept, the near-wake of a circular cylinder at a Reynolds number of 10^4 was characterized with a temporal resolution corresponding to 1% of the large-scale Kármán vortices, leading to resolution of small-scale structures of streamwise vorticity.

- The first characterization of simultaneous flow visualization and near-wake velocity spectra were obtained for amplitude and frequency-modulated excitation of a circular cylinder. New types of period-doubled phenomena leading to onset of disorganized behavior, as well as a highly modulated response of the near-wake were observed.

- The concept of timing of vortex formation relative to imposed cylinder oscillations was found to lead to a jump in phase, i.e. an abrupt change in timing of the initially shed vortex from the surface of the cylinder. This was characterized, for the first time, using instantaneous vorticity and streamline patterns, providing a quantitative basis for describing this well-known phenomena.

- The instantaneous three-dimensional structure of the near-wake of the cylinder with a mild defect was shown to lead to highly ordered patterns of out-of-plane vorticity concentrations, and a means for characterizing the detailed, complex behavior of forced dislocations in the near-wake.

- A localized nonuniformity in the form of a velocity defect or excess imposed by suction or blowing at a defined location on the span of the cylinder was found to lead to very large, rapidly broadening streamwise and cross-stream vorticity concentrations.

- Use of a fluid-strake concept involving unsteady blowing-suction through spiral hole patterns on the surface of the cylinder were found to dramatically alter the quasi-two-dimensional structure of the near-wake. When small amplitude oscillations of the cylinder were imposed, however, the effectiveness of this control technique was rapidly diminished.

- The importance of the thickness of the separating boundary layer relative to the thickness of a blunt body was established by artificially imposing suction at the trailing-edge. This suction led, in turn, to dramatic changes in the vortex formation in the near-wake region and, in some cases, its attenuation altogether.

16. SIGNIFICANT TRANSITIONS

- The techniques of high-image-density particle image velocimetry developed in our laboratory, focusing on laser scanning techniques, are now employed at a substantial number of university and government laboratories, both in this country and abroad. A relatively large number of visitors have come to our laboratories, both on a short-term and a long-term basis, to learn our techniques.

- Results of our investigations on detailed near-wake structure have been communicated to diverse audiences at meetings of the American Physical Society, American Society of Mechanical Engineers, International Union of Theoretical and Applied Mechanics, and other organizations. These communications have provided the framework for further investigations at a number of laboratories. Moreover, experimental results are being used by other groups to establish numerical simulations.

17. IMPACT OF RESEARCH

Knowledge of the instantaneous, quantitative structure of near-wakes of bluff bodies provide the basis for determining the instantaneous, unsteady loading using vorticity field concepts. This approach is meant to supplement, on a much more meaningful basis, traditional force and pressure measurement techniques. In addition, global, instantaneous images are essential for comparison with direct numerical simulation.

From a practical sense, techniques for generating and controlling three-dimensional flow structure are crucial in designing attenuation techniques, both of the passive and active type.

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2. The Defense Technical Information Center received the enclosed report (referenced below) which is not marked in accordance with the above reference.

FINAL REPORT
N00014-90-J-1510
TITLE: CONTROL OF TWO AND THRE-
DIMENSIONAL WAKE INSTABILITIES
FROM BLUFF-BODIES

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